Calibration, Refinement, and Application of the WEPP Model for Simulating Climatic Impact on Wheat Production

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Abstract. *Agricultural system models are useful tools for tailoring agricultural production systems to possible climate variations. The objectives of this work were: (1) to evaluate and calibrate the water balance and crop components of the Water Erosion Prediction Project (WEPP) model and to make improvements if necessary, and (2) to simulate hydrologic and crop responses to generated climate scenarios for winter wheat (*Triticum aestivum *L.). Precipitation, surface runoff, soil moisture, and wheat biomass collected between 1980 and 1996 on a 1.6 ha watershed near El Reno, Oklahoma, were used. Two contrasting (wet and dry) climate scenarios were generated using a climate generator (CLIGEN) for assessing the overall sensitivity of WEPP to climate variations. Optimized saturated hydraulic conductivity (K_s) agreed well with field−measured K_s, indicating that the infiltration routine of the model functioned properly. WEPP's original water use function substantially overpredicted plant water uptake and therefore was modified. The revised water use function resulted in better predictions of soil water balance, plant water stress, and biomass production. Predicted aboveground biomass agreed relatively well with measured data (model efficiency = 0.5). However, wheat grain yields were less well predicted because of inadequate adjustments to harvest index in the model. The general relationship between total aboveground biomass and growing−season evapotranspiration for winter wheat was reasonably simulated by the model. Model simulations under the generated wet and dry scenarios showed that each percent increase in growing−season precipitation would result in, on average, 3.38%, 0.34%, 0.73%, 1.09%, and 0.81% increases in surface runoff, plant transpiration, soil evaporation, deep percolation, and wheat grain yield, respectively, under the study conditions. This work has shown that WEPP is capable of simulating hydrologic and crop responses to climate variations.*

Keywords. *CLIGEN, Crop model, Impact assessment, Weather generator, WEPP.*

Advances in seasonal climate forecasts in the past decade provide a significant opportunity to improve agricultural production. However, the research on using seasonal climate forecasts to improve agricultural production is still young (Hammer et al., 2001; Hansen, 2002). Agricultural system models provide a useful tool for optimizing management decisions for a given climate variation or forecast. Before those models can be used for this purpose, their sensitivity to climate variations needs to be evaluated.

Most physically based agricultural system models such as the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) can be used to simulate crop responses to climate variations. The WEPP model is a physically based, continuous simulation computer program. It uses a stochastic CLImate GENerator (CLIGEN; Nicks et al., 1995) to generate daily weather input in the absence of measured data, a modified Green−Ampt equation to compute water infiltration, and a generic crop model to simulate crop development. A detailed model description can be found in Flanagan and Nearing (1995). A brief review of relevant components including weather generation, water balance, and crop growth is given below.

CLIGEN and USCLIMATE (Hanson et al., 1994) are the two commonly used daily weather generators (Johnson et al., 1996). CLIGEN generates daily precipitation, temperatures (maximum, minimum, and dew point), solar radiation, and wind velocity and direction. It takes a simple approach and generates each variable independent of other variables. Likewise, it generates each day independently (except for precipitation occurrence) and each month separately (it uses monthly statistics of daily values). Several evaluation studies using various versions of CLIGEN have been reported in the literature. Johnson et al. (1996) evaluated CLIGEN on six climatically dispersed U.S. sites and reported that the monthly and annual precipitation statistics were adequately replicated by the model. Headrick and Wilson (1997) evaluated CLIGEN at five Minnesota locations and found that CLIGEN reproduced daily precipitation amounts and temperatures reasonably well. Zhang and Garbrecht (2003) and Zhang (2004) evaluated a later improved version of CLIGEN (version 5.107) on four Oklahoma sites. They concluded that daily and monthly precipitation parameters, daily temperatures, and solar radiation were each adequately reproduced by CLIGEN. However, the day−to−day serial− and cross−correlations for and between daily temperatures, solar radiation, and precipitation were not properly simulated because of the aforementioned independence assumptions. The lack of proper correlation compounded by the less−than−

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perfect weather generation resulted in noticeable prediction errors in wheat yields for individual years, but the yield distribution, including mean and standard deviation, was satisfactorily reproduced, partially due to the stochastic nature of the generator (Zhang, 2004).

This finding suggests that CLIGEN is an adequate tool to use when probability distribution of crop yields is the primary focus. One possible application would be the use of seasonal climate forecasts to develop risk−based decision support information. In such applications (which are beyond the scope of this article and will be the focus of the future study), precipitation and temperature anomalies of monthly forecasts will be used to modify relevant CLIGEN input parameters for each month, and the modified parameters will then be used to generate daily time series to drive crop models. The independence assumptions of CLIGEN make it easier to adjust each month and each variable (e.g., temperature or precipitation) independently to "reproduce" each individual probabilistic forecast. Zhang (2003) has shown that CLIGEN is capable of reproducing seasonal sequences of monthly mean precipitation for different climate scenarios and is, therefore, a viable tool for analyzing crop production risks associated with a particular climate scenario derived from the probabilistic type of seasonal climate forecasts.

The WEPP (version 2001) water balance component is, in principle, similar to EPIC (Erosion/Productivity Impact Calculator; Sharpley and Williams, 1990) with some refinements in deep percolation and soil evaporation estimation (Savabi and Williams, 1995). Water infiltration is modeled using a modified Green−Ampt equation (Chu, 1978), evapotranspiration (ET) after Ritchie (1972), and deep percolation using a storage routing approach (Sharpley and Williams, 1990). Water infiltration and runoff generation were evaluated at eight climatically dispersed U.S. locations by Zhang et al. (1996), and their results indicated that the WEPP model simulated surface runoff reasonably well.

The WEPP crop growth component, which is similar to EPIC, is a generic type model (Arnold et al., 1995). The component uses a single model to simulate different crops by changing model parameter values. It uses the concept of daily accumulated heat index for simulating crop development, Monteith's approach for determining potential biomass (Monteith, 1977), water and temperature stresses for adjusting biomass production, and harvest index for partitioning grain yield. The water stress factor is estimated as a ratio of the water supply within effective rooting depth to the demand of potential plant transpiration. The temperature stress factor is a sine function of scaled daily average air temperature with no stress at the optimum growth temperature. No frost kill is simulated for winter crops. The model assumes optimal plant population and nutrient supply.

The objectives of this study were: (1) to evaluate and calibrate the WEPP water balance and crop growth components using measured climatology, hydrology, soil moisture, and winter wheat data and to make improvement if necessary, and (2) to simulate hydrologic and wheat productivity responses to CLIGEN−generated wet and dry climate scenarios using the calibrated WEPP model.

Materials and Methods

Watershed Description

One experimental watershed (FR−8), located at the Grazinglands Research Laboratory, 7 km west of El Reno, Oklahoma, was used in this study. The watershed is 80 m wide and 200 m long with a drainage area of 1.6 ha. The longitudinal slope of the watershed is approximately 3% to 4%. Soils are primarily silt loam with an average of 23% sand and 56% silt in the tillage layer. The climate at the location is characterized as semiarid to subhumid with large seasonal and interannual precipitation variability. The mean monthly precipitation is bimodal, with the primary peak occurring in May−June and the secondary peak in August−October. Annual precipitation, runoff, and relevant management information between 1980 and 1996 are given in table 1. A common regional annual winter wheat and summer fallow system was evaluated on the watershed. Conservation tillage systems with dominant disk operations were employed during the study period.

Table 1. Measured annual precipitation (P), surface runoff (Q), wheat straw and grain yields, nitrogen application rate (N), and general management information in an annual winter wheat and summer fallow system on a 1.6 ha watershed at El Reno, Oklahoma.[a]

Year	P (mm)	Q (mm)	Straw (kg/m^2)	Grain (kg/m^2)	N (kg/ha)	Planting (mm/dd/yy)	Harvest (mm/dd/yy)	Major Tillage and Management Operation
1980	626	17	0.441	0.203	76	10/3/79	6/23/80	7/15 stubble mulch plow; 10/1 chisel
1981	863	4	0.181	0.129	58	10/3/80	6/9/81	9/18 and 12/18 light disk
1982	756	24	0.466	0.201	134	12/25/81	6/17/82	7/28 stubble mulch plow; 10/5 TD
1983	1061	146	N/A	N/A	0	10/6/82	N/A	Killed wheat and planted oat in March
1984	736	38	0.594	0.148	58	11/17/83	6/22/84	7/26, 8/27, and 10/4 OD
1985	905	104	N/A	N/A	125	10/23/84	6/7/85	Lots of cheat; 7/26 chisel; 8/22 TD
1986	1122	214	N/A	N/A	52	12/23/85	N/A	Baled for hay; 8/12, 9/11, 10/16, and 10/30 OD
1987	1044	139	0.497	0.144	39	10/31/86	6/4/87	6/28, 7/23, and 10/8 OD
1988	718	74	0.990	0.325	97	10/9/87	6/14/88	7/6 OD; 10/25 TD
1989	981	110	0.390	0.208	123	12/26/88	6/20/89	7/28 and 8/22 OD; 9/28 TD
1990	909	169	0.573	0.197	52	9/29/89	6/7/90	7/13 and 8/24 OD; 10/2 three−point disk
1991	848	6	0.582	0.196	11	10/5/90	5/31/91	6/27, 7/9, 8/29, and 9/27 three−point disk; 7/16 OD
1992	894	141	0.502	0.192	52	9/30/91	6/11/92	7/6 and 7/30 three−point disk; 9/29 and 10/1 OD
1993	1003	172	0.932	0.261	85	10/2/92	6/16/93	8/27 sweep plow; 9/27 and 10/6 OD
1994	843	140	0.759	0.244	103	10/12/93	6/14/94	6/24 sweep plow; 9/30 disk
1995	1011	216	0.697	N/A	103	10/11/94	6/20/95	Lots of rye; 7/11 sweep plow; 10/13 disk
1996	679	37	N/A	0.146	50	10/25/95	6/17/96	Straw not measured; 11/12 moldboard plow

[a] N/A = not available, TD = tandem disk, and OD = offset disk.

Data Collection

Four weighing rain gauges (203.2 mm diameter catch) were used to record precipitation data. Mean values were used to build the measured climate input file for the period of 1980 to 1996. An H−flume with a float and mechanical water−level recorder was used to measure runoff flow rates. Stage height in the flume was converted into water discharge using a calibrated rating table for the flume. Prior to harvest, at least six samples were randomly taken on the watershed between 1980 and 1995, when appropriate, to determine total aboveground biomass and grain yields (table 1). Soil tests were conducted each year, and nutrient deficiencies and soil pH problems were corrected as needed prior to fall planting.

The soil moisture profile was measured with a neutron probe at 15 cm depth increments (up to 1.3 m in depth) at the upper, middle, and lower positions of the watershed at approximately 10−day intervals from January 1979 to December 1982 and from September 1985 to December 1994. The neutron probe was in−situ calibrated to the soil type in the watershed around 1980. However, a drop in the standard count happened to the probe at the beginning of 1990. Due to the shift, the absolute soil moisture measurement after 1990 was inaccurate, but the relative soil moisture change was considered acceptable because a somewhat constant shift in the soil moisture measurements was expected. Thus, the neutron data after 1990 were not used to evaluate soil moisture predictions of the WEPP model, but they were used to compute soil moisture depletion between planting and harvest dates, which was used to estimate measured ET.

Compilation of Measured WEPP Input Files

Four input files (i.e., slope, soil, climate, and crop management) are needed to run the WEPP model. Measured slope profile and soil properties (table 2) were used to build the slope and soil input files. Daily precipitation measured at the watershed location from 1980 to 1996 and daily maximum and minimum temperatures measured at the National Weather Service El Reno station (within 7 km) were directly used in the climate file. The missing variables, including solar radiation, wind velocity and direction, dew point temperature, and internal storm patterns, were generated using CLIGEN V5.107 for the El Reno station. Since 1994, solar radiation, wind velocity and direction, and temperatures (maximum, minimum, and dew point) have been measured at a nearby Oklahoma Mesonet station (within 1 km), and those data were used in the measured climate file instead of generated values. Actual crop management and tillage operations from 1980 to 1996 (table 1) were used to construct the WEPP crop management file for the watershed.

Table 2. Average soil properties used in this study.

Depth (cm)	Sand (%)	Clay (%)	Organic Matter (%)	Bulk Density (g/cm^3)	Field Capacity (cm^3/cm^3)	Wilting Point (cm^3/cm^3)
0−15	24.1	23.1	3.2	1.27	0.375	0.148
15−30	24.6	24.7	2.5	1.38	0.350	0.156
30−45	22.5	31.0	2.1	1.50	0.360	0.187
45−60	20.1	37.2	1.8	1.66	0.372	0.235
60−75	19.8	39.2	1.8	1.69	0.379	0.246
75−90	20.0	40.3	1.4	1.70	0.393	0.255
90−105	21.0	40.2	1.4	1.73	0.392	0.256
105−120	23.4	40.1	1.3	1.73	0.399	0.259
120−140	24.1	40.2	1.3	1.76	0.402	0.268

Model Calibration and Evaluation

The key WEPP parameters that were calibrated in this study were effective hydraulic conductivity (K_s), water stress factor, harvest index, and energy−biomass ratio. A computer program was developed to automatically optimize the Green−Ampt effective hydraulic conductivity under the WEPP continuous simulation mode using measured data during 1980−1996. A total of 374 storms including all runoff−producing events were used in the optimization. The objective function was the sum square error (SSE), calculated as the sum of the squared differences between measured and predicted event runoff depths. After each WEPP run, SSE was calculated, and a new K_s along with a new search domain was chosen by comparing the current and previous SSE. The objective function was minimized iteratively until a preset convergence criterion of 0.1% was met. The predefined search domain was between 0.07 and 15 mm/h. The optimization procedure was conducted in such a way that only the K_s parameter was altered prior to each WEPP run.

Water stress factor in WEPP is modeled as a supply−to−demand ratio. Water supply is the sum of plant water use from all soil layers within the effective rooting depth. The water use function currently used in WEPP assumes that the rate of plant water uptake decreases exponentially with soil depth, as a result of exponential decrease of root density with depth. However, it allows plants to fully compensate for water deficit in one layer by using more water from other layers. This protocol has a tendency of excessive water uptake from deeper soil layers (Sharpley and Williams, 1990). A more generic water use function, similar to that used in EPIC (Sharpley and Williams, 1990), was incorporated into WEPP. The new function uses a water deficit compensation factor, which varies from 0 to 1 and allows a full range of water deficit compensation. A value of one allows full compensation, which is virtually identical to the current WEPP model. A value of zero allows no compensation. After the initial test, a value of zero was found to produce daily soil water contents that were in closer agreement with the neutron soil moisture data.

For winter wheat, a number of parameter values (e.g., leaf area index = 5, base temperature = 4°C, and optimum growth temperature = 15°C) were directly taken from those recommended by Arnold et al. (1995). A harvest index of 0.32 was derived from the measured wheat data, and a rooting depth of 1.3 m was assumed (Jim Kiniry, personal communication). With the optimized K_s of 7.95 mm/h and with no deficit compensation, a biomass−energy conversion ratio of 25 g/kJ was arrived by manually matching predicted and measured mean aboveground biomass at harvest.

Due to the dependent nature between the hydrology and plant growth components, soil water balance was evaluated prior to crop parameter calibration. For better quality control, this calibration cycle (including K_s optimization) was repeated. The final calibrated parameter values, as mentioned above, along with other measured data were then used to run the WEPP model. Model outputs of daily soil water dynamics were compared to the neutron data measured between September 1985 and December 1989. The WEPP biomass−ET relationship was evaluated against the measured relationship. Year−to−year predictability values of aboveground biomass and grain yields were evaluated against measured data. Finally, the potential responses of wheat grain yields to generated climate scenarios were simulated using the refined WEPP model under the conditions for which the model was trained.

Model efficiency is a good measure of model prediction relative to measured data (Zhang et al., 1996). The model efficiency (ME), as defined by Nash and Sutcliffe (1970), was calculated as:

$$ME = 1 - \frac{\sum (Y_{obs} - Y_{pred})^2}{\sum (Y_{obs} - Y_{mean})^2} \qquad (1)$$

where

Y_{obs} = measured value

Y_{pred} = predicted value

Y_{mean} = measured mean.

ME can range from $-\infty$ to 1. If ME = 1, the model produces the exact prediction for each data point. A zero value of ME implies that a single mean measured value is as good an overall predictor as the model. A negative value of ME indicates that the measured mean is a better predictor than the model.

Generation of Climate Scenarios

To simulate the potential impacts of seasonal climate variations on soil hydrology and wheat productivity, historical weather records of the El Reno station between 1950 and 1999 were used. The records encompassed relatively dry (1950−1974) and wet (1975−1999) periods (fig. 1). The mean annual precipitation was 750 mm in the dry period and 850 mm in the wet period. The measured daily precipitation and maximum and minimum temperatures in each period were used to derive CLIGEN input parameters for each period using a CLIGEN−support parameterization program. The derived parameters (mainly means and standard deviations) were then input into CLIGEN to generate 50 years of daily weather data to represent that period. The two generated daily weather series are referred to as the "dry" and "wet" scenarios hereafter.

Simulation of Climatic Impact

For simplicity, a common regional one−year rotation of winter wheat and summer fallow was used. In the simulation, winter wheat was planted on October 15 and harvested on June 20 each year, and the field was chiseled on July 1 and disked on the first days of August, September, and October. The calibrated WEPP model was run for 50 years each for the generated dry and wet scenarios using the generic management file along with the measured soil and slope files compiled for the watershed. Initial soil moisture content at planting was not reset each year during the simulation because the two generated climate scenarios represented relatively dry and wet periods of the historical climate sequences. Output of crop yield and selected hydrologic variables were compared between the two scenarios.

Results and Discussion

Surface Runoff

The optimized effective saturated hydraulic conductivity (K_s) was 7.95 mm/h for the watershed. Vogel et al. (2001) reported that the mean saturated infiltration rate measured using a double−ring infiltrometer during 1999 was 8.4 mm/h for the watershed, with the 25 and 75 percentiles being 4.4 and 10.0 mm/h, respectively. There might be some concern over the temporal disparity between the optimized and double−ring measured K_s due to changes in tillage systems, but the close agreement between these estimates may serve as an overall indicator that the WEPP infiltration component functioned adequately under the study conditions. The WEPP−predicted annual runoff using the optimized K_s is plotted with the measured runoff in figure 2. The ME between measured and predicted annual runoff was 0.31, and the coefficient of determination (r^2) was 0.56. The WEPP model overpredicted annual surface runoff. This might be partially caused by preferential flow. Soils in the watershed contain swelling clay and crack upon drying. The preferential flow through cracks, which enhances water infiltration, is not modeled in WEPP. The lack of the preferential flow treatment might also have contributed to the large variability of the predicted annual surface runoff.

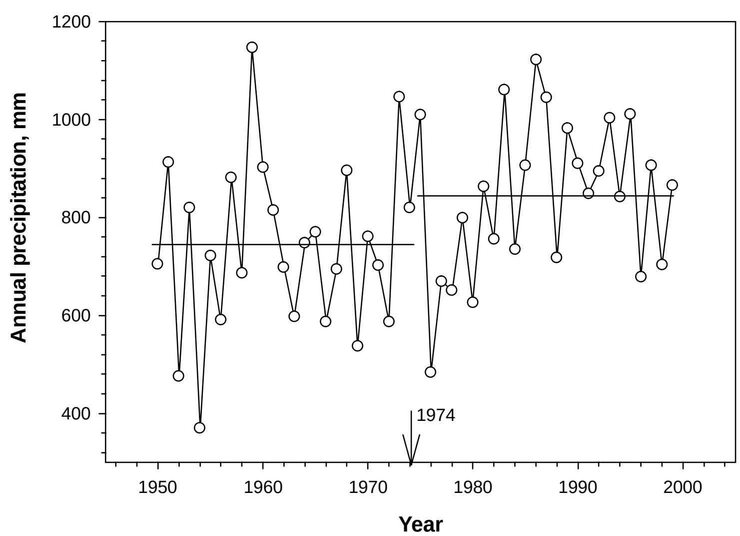


Figure 1. Measured annual precipitation at El Reno, Oklahoma, during 1950−1999 (horizontal lines indicate the means of the dry and wet periods).

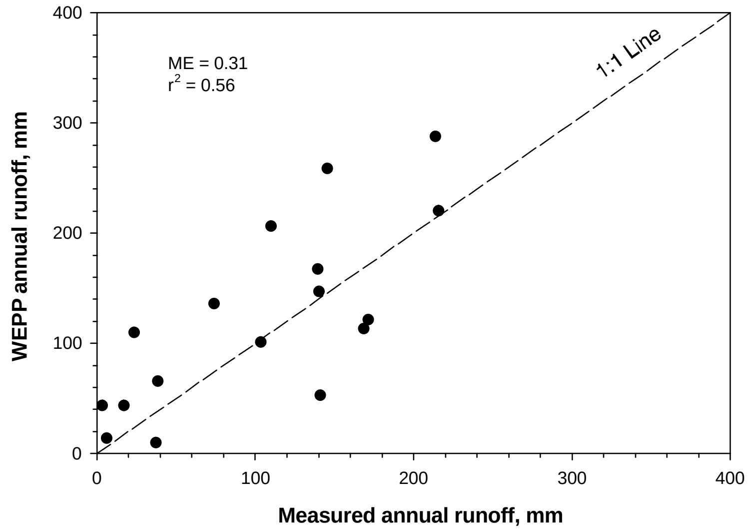


Figure 2. Relationship between measured and WEPP−simulated annual runoff depths using optimized saturated hydraulic conductivity on the watershed for the period of 1980−1996.

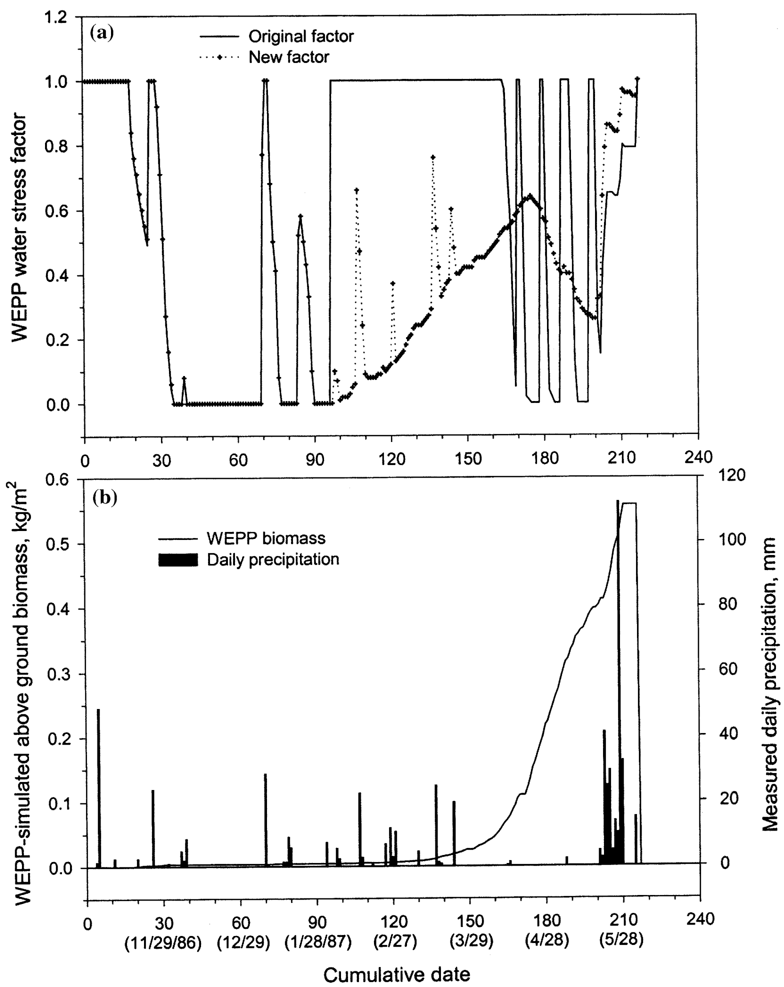
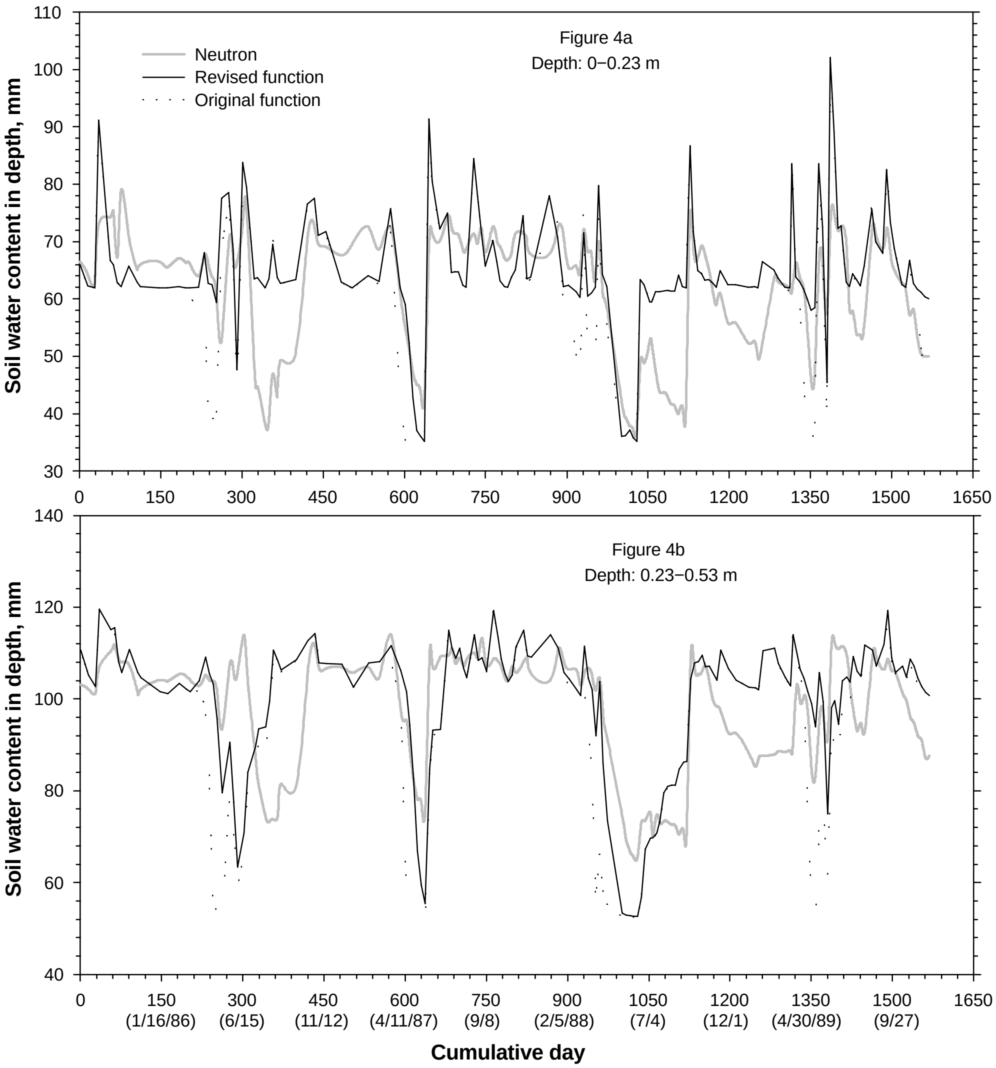


Figure 3. New and original water stress factors, daily precipitation, and aboveground biomass during the 1987 growing season.

Water Stress Factor

The new water stress factor calculated with the revised water use function that allows no water deficit compensation, along with the original stress factor that allows full compensation, is plotted in figure 3a, and daily precipitation amounts and a simulated growth curve representative of both water use functions are shown in figure 3b. The water stress factor ranges from 0 to 1. A value of one means no stress limitation on plant growth, while zero gives maximum limitation and allows no biomass growth. The new stress



Figures 4a and 4b (continued).

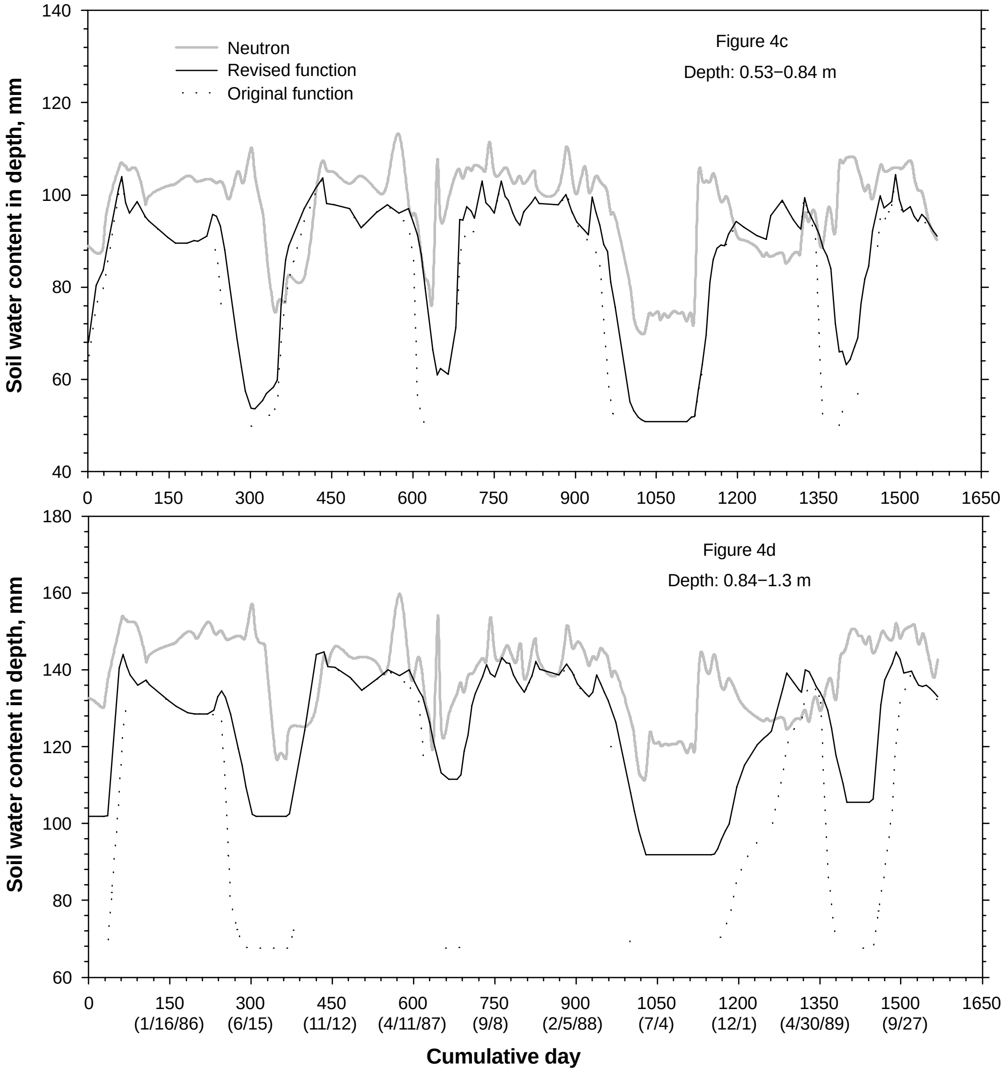
factor corresponded to daily precipitation and biomass growth more reasonably than did the original factor.

SOIL WATER DYNAMICS

Measured and simulated soil water contents in response to both water use functions are plotted by soil layer in figure 4. In general, the annual cycles of soil moisture drawdown by winter wheat and recharge afterwards in the top 0.5 m soil layers (figs. 4a and 4b) were well simulated by both functions most of the time. However, the magnitude of annual soil water use below the 0.5 m depth was overpredicted by both water use functions (figs. 4c and 4d), although the overprediction was greatly reduced with the revised function, especially in the 0.84 to 1.3 m depth. The mean annual maximum changes in total soil water in the 1.3 m soil profile (fig. 4e) were 136 mm for neutron data, 166 mm for simulated data with the revised water use function, and 216 mm with the original WEPP function (under similar biomass production). The two soil moisture peaks on September 19, 1988, and June 6, 1989 (fig. 4e) were badly missed by both functions. This was because significant amounts of rain (173 mm for September 19 and 214 mm for June 16) fell within a week, and WEPP considerably overpredicted surface runoff. Even with the new water use function that allows no water deficit compensation, simulated wheat withdrew, on average, 30 mm more soil water from the soil profile each year than was indicated by the neutron measurement. The overall results suggest simulated wheat would be somewhat less sensitive to water stress because of the model's greater ability to tap soil water reserve in deeper soil layers. The impact of this bias on crop simulation is elaborated later.

CROP COMPONENT EVALUATION

The revised WEPP model with the new water use function was run using the calibrated parameter values along with the other measured input files compiled for the watershed. The predicted and measured aboveground biomass values at harvest are shown in figure 5. The predicted and measured biomass agreed reasonably well. The ME was 0.26 and r^2 was 0.37. However, the ME and r^2 increased to 0.50 and 0.52, respectively, when the year 1984 was excluded. Double crops were grown in 1983, and WEPP did not properly simulate the double crops and considerably overpredicted plant water uptake during 1983. This might have some bearing on 1984's biomass prediction. The measured and predicted grain yields are plotted in figure 6. The ME was 0.16 and r^2 was 0.54. Each year, WEPP estimates grain yield by multiplying aboveground biomass at harvest by an internally adjusted harvest



Figures 4c and 4d (continued).

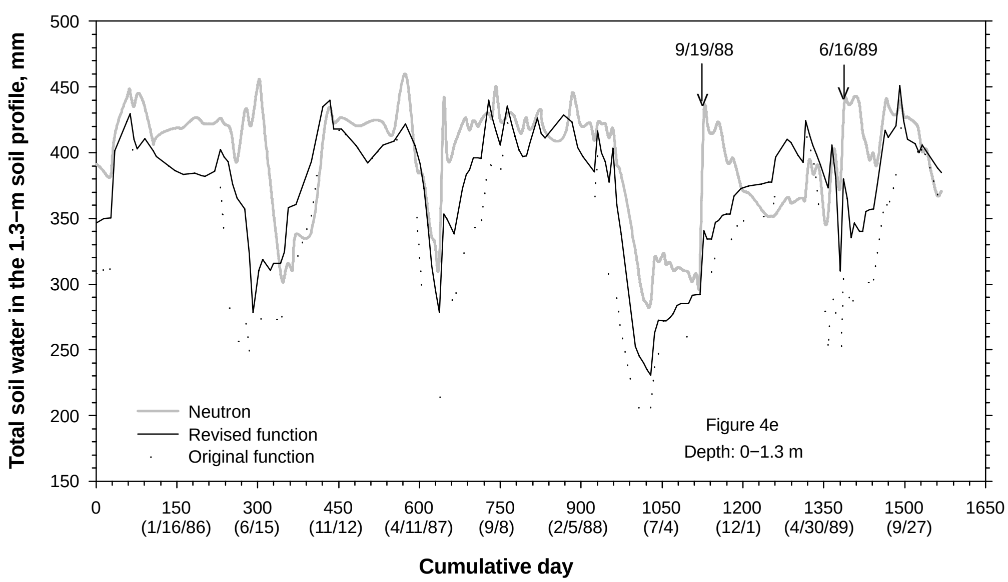


Figure 4e.

Figure 4. Neutron−measured vs. WEPP−simulated soil moisture contents using both revised and original water use functions for the period of September 1985 to December 1989.

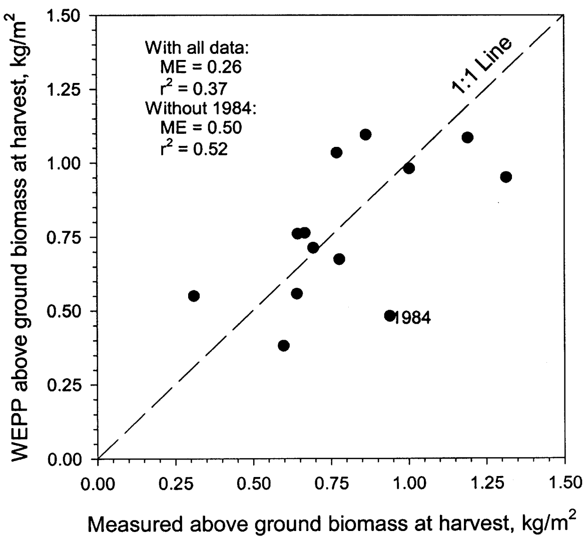


Figure 5. Measured and simulated aboveground wheat biomass at harvest using the calibrated WEPP model on the watershed.

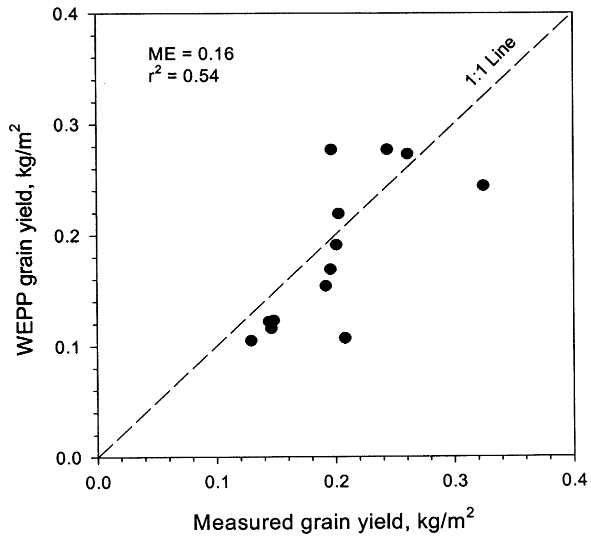


Figure 6. Measured and simulated wheat grain yields using the calibrated WEPP model on the watershed.

index. Thus, any inadequate adjustment to the harvest index will lead to errors in grain yield estimation. Water stress adjustment to the harvest index at a critical growth stage like anthesis is considered in WEPP, but many factors that affect the harvest index such as weeds, lodging, hail, and diseases are not modeled in WEPP. In this study, the WEPP−adjusted harvest index ranged from 0.2 to 0.3, while the measured harvest index ranged from 0.2 to 0.4. Any improvement in harvest index adjustments would definitely improve grain yield prediction.

The maximum biomass ranges (maximum minus minimum) were about 1.01 and 0.71 kg/m^2 for the measured and predicted biomass, respectively. The coefficients of variation were 33% for the measured and 31% for the predicted biomass. The underprediction of the biomass variability could be caused by model's inadequate responses of plant growth to favorable and adverse growth conditions. It could be also caused by factors such as weeds, diseases, pests, and frost, which contribute to overall measured variance but are not modeled in WEPP. Such simplifications in representing reality inevitably lead to undesirable reduction in variability in the model output, and this reduction in variability needs to be quantified and corrected before more reliable risk analysis can be made on simulated crop yields.

Measured ET during the growing season was estimated by: precipitation − measured runoff − neutron moisture at harvest + neutron moisture at planting. The WEPP ET between planting and harvest dates was calculated as: actual precipitation − predicted runoff − predicted deep percolation − predicted soil water at harvest + predicted soil water at planting (equivalent to the sum of predicted soil evaporation and plant transpiration). Contribution of deep percolation was not deducted from the measured ET because it was not measured on the watershed. The measured and WEPP biomass−ET relationships are shown in figure 7. The r^2 values were 0.364 and 0.695 for the measured and WEPP relationships, respectively. Both regression slopes were numerically close, and were not statistically different at $P = 0.05$ because of the large variability in the data sets. The slopes of these plots were by definition the water use efficiency, which reflected biomass production per unit ET consumption for winter wheat at the location. The overall trends of the measured and predicted biomass−ET relationships agreed fairly well. This could be because the nutrient stress, which the WEPP model does not simulate, was largely eliminated from the experimental data by annual soil testing, as mentioned earlier.

Simulated Hydrologic and Yield Responses to Climate Scenarios

Growing−season surface runoff (Q), plant transpiration (E_p), soil evaporation (E_s), and deep percolation (D_p) simulated for the dry and wet climate scenarios using the refined WEPP model increased with precipitation (table 3). The average increases, calculated using the mean quantities of both scenarios, were approximately 27% for the growing−season precipitation (P), 91% for Q, 9% for E_p, 20% for E_s, 29% for D_p, and 22% for grain yield. Each percent increase in P resulted in, on average, an increase of 3.4% in Q, 0.34% in E_p, 0.73% in E_s, 1.09% in D_p, and 0.81% in grain yield. These relative changes or overall sensitivities reflect how hydrology and wheat production may actually respond to a shift or change in climate at the location. The greater increase in surface runoff indicated a greater sensitivity of surface runoff to precipitation increase on the watershed. The coefficients of variation for P, Q, E_p, E_s, and D_p were correspondingly 25%, 124%, 16%, 32%, and 55% in the dry scenario, and 22%, 77%, 18%, 30%, and 50% in the wet scenario. The variabilities excluding E_p were generally greater in the dry scenario than in the wet scenario, especially for Q and D_p. Moreover, the results showed that wheat grain yield was quite sensitive to precipitation increase. It should be noted that the actual yield sensitivity to climate scenarios could be greater than that which is estimated here. As pointed out earlier, the WEPP model appeared to be less sensitive to water stress due to its overuse of soil water from deeper soil layers.

Probability distributions of the simulated wheat grain yields are shown in figure 8 for the dry and wet scenarios. The wheat yields of the wet scenario shifted considerably to higher yields, and the shifts increased with the cumulative probability. The predicted yields were more widely spread in

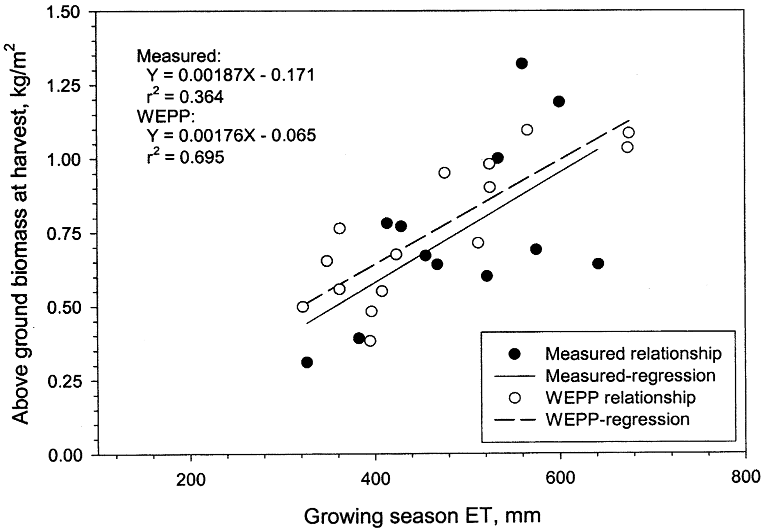


Figure 7. Measured and simulated relationships between aboveground biomass at harvest and growing−season ET on the watershed (WEPP ET: 1981 through 1996 except 1983; measured ET: 1980 through 1982 and 1986 through 1994).

Table 3. Mean ±1 SD of measured growing−season precipitation (P) and WEPP−simulated growing season runoff (Q), plant transpiration (E_p), soil evaporation (E_s), deep percolation (D_p), total soil water in the 1.4 m profile at planting (SW_p) and harvest (SW_h), and wheat grain yield for dry and wet scenarios.[a]

Climate Scenario	P (mm)	Q (mm)	Ep (mm)	Es (mm)	Dp (mm)	SW_p (mm)	SW_h (mm)	Grain Yield (kg/m^2)
Dry	449 ±113	34 ±42	393 ±61	95 ±30	60 ±33	401 ±36	282 ±19	0.191 ±0.037
Wet	569 ±128	64 ±49	429 ±76	113 ±34	78 ±39	399 ±36	295 ±24	0.232 ±0.050

[a] Lateral soil water discharge was near zero for both cases, and therefore neglected.

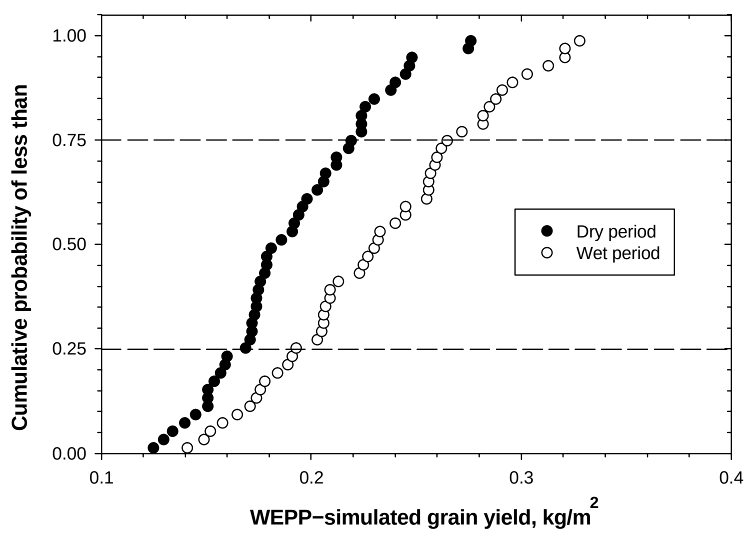


Figure 8. Cumulative probability distributions of simulated wheat grain yields using calibrated WEPP model for the wet and dry climate scenarios on the watershed.

the wet scenario than in the dry scenario, indicating an increased variability or uncertainty in wheat yield in the wet period. The coefficients of variation were 19% for the dry scenario and 22% for the wet scenario. The interquartile ranges (between 25 and 75 percentiles), which is another measure of variability, were between 0.169 and 0.219 kg/m^2 for the dry period and between 0.193 and 0.265 kg/ m^2 for the wet period. That is, there is a 50% chance that wheat yield would be between 0.169 and 0.219 kg/m^2 for a given year in the dry scenario and between 0.193 and 0.265 kg/ m^2 for a given year in the wet scenario. The considerable overlap between the two interquartile ranges resulted from occurrences of wet years in the dry period and occurrences of dry years in the wet period.

Simulated grain yields are plotted with growing−season P and plant−available soil water for both scenarios in figure 9. The plant−available water was the sum of soil moisture reserve in the 1.4 m profile at planting (i.e., total soil water above wilting point) and infiltrated rainwater during the growing season as predicted by the WEPP model. In general, simulated yield increased linearly with the growing−season P and plant−available water. However, the linear correlation

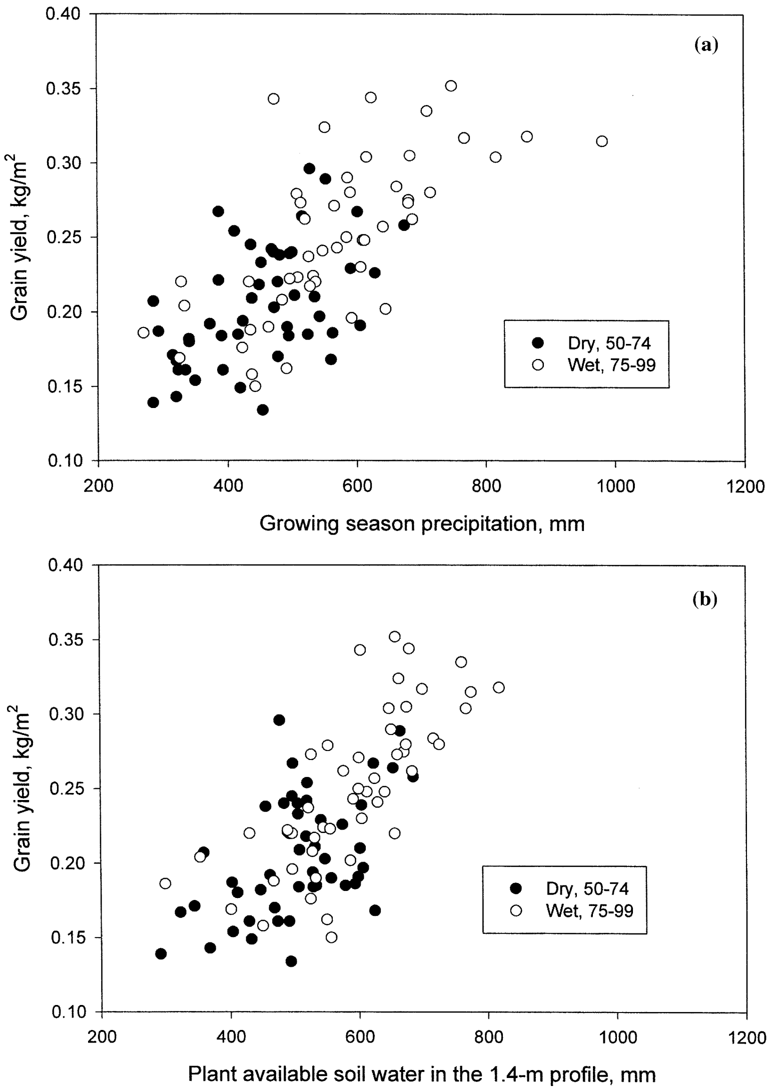


Figure 9. Simulated relationships between wheat grain yield and (a) growing−season precipitation and (b) plant−available soil water for the dry and wet scenarios.

was much stronger with the plant−available water than with the growing season P. The correlation coefficients with the growing−season P were 0.505 in the dry scenario and 0.686 in the wet scenario (fig. 9a), and those with the plant−available water were 0.513 and 0.744 (fig. 9b), respectively. The yield variation for a given plant−available water value in figure 9b may be attributed to the timing of precipitation as well as year−to−year temperature variation during the growing season.

CONCLUSIONS

The optimized saturated hydraulic conductivity agreed well with the double−ring measured saturated infiltration rate on the watershed, suggesting that the WEPP infiltration routine functioned properly under the study conditions. The calibrated model predicted annual runoff moderately well. The revised water use function that allows variable water deficit compensation between soil layers (no compensation was allowed in this particular work) considerably improved WEPP's overall predictability of soil water balance, plant water stress factor, and biomass prediction. The new water use function, which is more generic than the one used in WEPP, can be readily calibrated as needed to simulate various soils and crops. The revised model satisfactorily simulated soil water balance in the top 0.5 m layer, but it had a slight tendency to underpredict soil water content below the 0.5 m depth due to the overprediction of water uptake.

Predicted aboveground biomass agreed relatively well with measured biomass. The model efficiency (ME), excluding 1984, was 0.50. Compared to biomass prediction, wheat grain yield was less well predicted (ME = 0.16), partially because of the insufficient adjustment to the harvest index in the model. The calibrated model satisfactorily approximated the measured relationship between total aboveground biomass and growing−season ET.

Model simulation under the dry and wet scenarios revealed that each percent increase in growing−season precipitation would, on average, result in 3.38% increase in surface runoff and 0.81% increase in wheat grain yield. These results showed that predicted surface runoff was sensitive to precipitation increase under the study conditions, and simulated wheat yield was quite responsive to precipitation.

This work indicates that the WEPP model is capable of simulating hydrologic and wheat responses to climate variations.

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